

Utility of a Special Second Scalar Doublet

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Abstract

This Brief Review deals with the recent resurgence of interest in adding a second scalar doublet (η^+, η^0) to the Standard Model of particle interactions. In most studies, it is taken for granted that η^0 should have a nonzero vacuum expectation value, even if it may be very small. What if there is an exactly conserved symmetry which ensures $\langle \eta^0 \rangle = 0$? The phenomenological ramifications of this idea include dark matter, radiative neutrino mass, leptogenesis, and grand unification.

The Minimal Standard Model (SM) of particle interactions has only one scalar doublet $\Phi = (\phi^+, \phi^0)$. As ϕ^0 acquires a nonzero vacuum expectation value (vev) v , the famous Higgs mechanism allows the W^\pm and Z^0 gauge bosons to become massive. At the same time, of the original four degrees of freedom in Φ , only one [i.e. the Higgs boson $h = \sqrt{2}(\text{Re}\phi^0 - v)$] remains. What happens if more scalar doublets are added? One possibility is to allow for new sources of CP nonconservation, as was pointed out a long time ago [1, 2]. Another is to allow the SM to be extended to include supersymmetry, as is well-known. In these and other investigations of the two (or more) scalar doublets [3], the usual implicit assumption is that both scalar doublets have vev's. This is necessary in the Minimal Supersymmetric Standard Model (MSSM) because one scalar doublet couples only to u quarks, and the other only to d quarks and charged leptons. However, in the context of the SM alone, a second scalar doublet, call it $\eta = (\eta^+, \eta^0)$, is not required to have any vev, in which case an exactly conserved Z_2 discrete symmetry may be defined, as pointed out many years ago [4], implying a stable particle. This idea has been revived recently, together with some new developments.

Following Ref. [4], consider the simplest possible discrete symmetry, i.e. Z_2 , under which η is odd and all SM particles are even, it was pointed out first in Ref. [5] that either $H^0 = \sqrt{2}(\text{Re}\eta^0)$ or $A^0 = \sqrt{2}(\text{Im}\eta^0)$ may be considered as a dark-matter candidate. For this to work, there has to be a splitting in mass between the two, otherwise they become just one particle exactly like the scalar neutrino of the MSSM, which can interact with nuclei through the Z^0 boson, having a cross section some eight orders of magnitude larger than the present experimental limit. If the mass splitting is larger than about 1 MeV, Z^0 exchange is forbidden by kinematics in these underground direct-search experiments based on the elastic scattering of dark matter with nuclei. The source of this mass splitting is the allowed term $(\lambda_5/2)(\Phi^\dagger\eta)^2 + H.c.$, where $\Phi = (\phi^+, \phi^0)$ is the SM Higgs doublet. This minimal version of dark matter has also been proposed [6], starting with a different perspective, and studied

seriously [7]. Its astrophysical [8] and collider [9] signatures have also been investigated. The mass of the dark-matter candidate is likely to be between 45 and 75 GeV, with detection in direct-search experiments at the level of two orders of magnitude below present bounds [6, 7]. Its production at the Large Hadron Collider (LHC) is from $pp \rightarrow Z^0 \rightarrow A^0 H^0$ and may be detected through the decay $A^0 \rightarrow H^0 l^+ l^-$ [6, 9].

With the assumed existence of the special scalar doublet η , which may be called the *dark* scalar doublet (which is more suitable than the name “inert Higgs doublet” because it is neither inert since it has electroweak interactions, nor a “Higgs” doublet since it has no vev), other particles which are odd under Z_2 may be contemplated. Indeed, in that first paper [5] already mentioned, three heavy neutral Majorana fermions N_i were proposed which are also odd under Z_2 . This means that the Yukawa terms $(\nu_i \phi^0 - l_i \phi^+) N_j$ are forbidden, so that N_i are not Dirac mass partners of ν_i . On the other hand, the Yukawa terms $(\nu_i \eta^0 - l_i \eta^+) N_j$ are allowed, so that one-loop radiative Majorana seesaw masses for ν_i may be generated, as shown in Fig. 1.

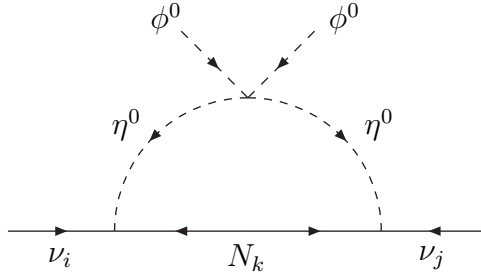


Figure 1: One-loop generation of neutrino mass.

In the canonical seesaw mechanism, doublet neutrinos acquire mass through mixing with heavy singlet neutral fermions (often called right-handed neutrinos). Here there is no mixing at all. Radiative masses appear from electroweak symmetry breaking, i.e. $\langle \phi^0 \rangle = v$, which is also the source of $A^0 - H^0$ mass splitting. In other words, the same mechanism which

allows H^0 to be a suitable dark-matter candidate also allows ν_i to acquire nonzero radiative seesaw masses. Specifically, the diagram of Fig. 1 is exactly calculable from the exchange of H^0 and A^0 , i.e.

$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{h_{ik}h_{jk}M_k}{16\pi^2} \left[\frac{m_H^2}{m_H^2 - M_k^2} \ln \frac{m_H^2}{M_k^2} - \frac{m_A^2}{m_A^2 - M_k^2} \ln \frac{m_A^2}{M_k^2} \right], \quad (1)$$

where M_k is the Majorana mass of N_k . Using $m_H^2 - m_A^2 = 2\lambda_5 v^2$ and $m_0^2 \equiv (m_H^2 + m_A^2)/2$, and assuming $m_0^2 \ll M_k^2$, then

$$(\mathcal{M}_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2} \sum_k \frac{h_{ik}h_{jk}}{M_k} \left[\ln \frac{M_k^2}{m_0^2} - 1 \right]. \quad (2)$$

This formula shows that smaller values of M_k than those of the canonical seesaw mechanism may be used for generating the same neutrino masses.

In canonical leptogenesis [10], the decay $N \rightarrow \phi^\pm l^\mp$ generates a lepton asymmetry in the early Universe which gets converted into a baryon asymmetry through sphalerons. Here the decay is instead $N \rightarrow \eta^\pm l^\mp$, which connects the existence of dark matter to the baryon asymmetry of the Universe [11]. In the minimal supersymmetric version [12] of this model, there is also a bonus. Because of the radiative suppression of Eq. (2), the mass of the lightest N_i may now be safely below the Davidson-Ibarra bound [13] of about 10^9 GeV.

Another very important consequence is the emergence of two or more types of dark matter. After all, there is no fundamental principle which requires that there is only one type of dark matter [14, 15]. A generic discussion of this possibility has recently appeared [16].

Suppose the lightest particle odd under Z_2 is N_k , then it may also be a dark-matter candidate [17], but severe constraints from lepton flavor violating processes such as $\mu \rightarrow e\gamma$ become important because N_k annihilates only through its Yukawa couplings to leptons and its proper relic abundance requires those to be large. One way to escape such constraints is

to allow N_k to have additional interactions from an extra $U(1)$ gauge group [18] or an extra scalar singlet [19].

Since $\mu \rightarrow e\gamma$ is automatically allowed in this class of models, the muon anomalous magnetic moment must also have a contribution. To suppress the former and to enhance the latter, a variant of the proposed mechanism of radiative neutrino mass has also been proposed [20]. Here lepton number is considered as a global $U(1)_L$ symmetry with heavy neutral fermion singlets N_i and N_i^c transforming as 1 and -1 respectively. They then have allowed Dirac masses, but they are also odd under Z_2 . Together with the usual η doublet and a new scalar charged singlet χ^- , the Yukawa terms $(\nu_i\eta^0 - l_i\eta^+)N_j^c$ and $l_i^c\chi^-N_j$ are allowed, resulting in enhanced contributions to the muon anomalous magnetic moment. As for neutrino mass, it again occurs in one loop, but only if $U(1)_L$ is broken down to $(-)^L$, which may be accomplished by the small explicit soft terms N_iN_j and $N_i^cN_j^c$. Hence the formula for radiative neutrino mass has one more suppression, which argues for the Dirac masses of (N, N^c) to be of order TeV. Leptogenesis may also be implemented by the decay of the lightest such pair.

Given the structure of the minimal dark scalar doublet model or its supersymmetric extension, the next question to ask is whether it has a natural grand unification. There have been two developments. One is to consider its supersymmetric $SU(5)$ completion [21]. This means adding the superfields

$$\underline{5} = h(3, 1, -1/3) + (\eta_2^+, \eta_2^0)(1, 2, 1/2), \quad (3)$$

$$\underline{5}^* = h^c(3^*, 1, 1/3) + (\eta_1^0, \eta_1^-)(1, 2, -1/2), \quad (4)$$

both of which are odd under Z_2 . Conventionally, the existence of $h(h^c)$ in the $\underline{5}(\underline{5}^*)$ representations of $SU(5)$ is considered dangerous because it would mediate rapid proton decay. However, the new Z_2 symmetry used here for dark matter also serves the purpose of conserving baryon number and preventing proton decay. The signature of this model is the decay

$h \rightarrow de^- \eta_2^+$ or $de^+ \eta_2^-$. The production of $h\bar{h}$ will thus result in same-sign dileptons plus quark jets plus missing energy.

Another possible embedding of the dark scalar doublet model is into the supersymmetric $E_6/U(1)_N$ model [22]. There are now three $\underline{27}$ representations of superfields, and two Z_2 discrete symmetries are imposed [23], as shown below.

Table 1: Particle content of $\underline{27}$ of E_6 under $SU(3)_C \times SU(2)_L \times U(1)_Y$ and $U(1)_N$.

Superfield	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_N$
$Q = (u, d)$	$(3, 2, 1/6)$	1
u^c	$(3^*, 1, -2/3)$	1
e^c	$(1, 1, 1)$	1
d^c	$(3^*, 1, 1/3)$	2
$L = (\nu, e)$	$(1, 2, -1/2)$	2
h	$(3, 1, -1/3)$	-2
$\bar{E} = (E^c, N_E^c)$	$(1, 2, 1/2)$	-2
h^c	$(3^*, 1, 1/3)$	-3
$E = (\nu_E, E)$	$(1, 2, -1/2)$	-3
S	$(1, 1, 0)$	5
N^c	$(1, 1, 0)$	0

Table 2: Particle content of $\underline{27}$ of E_6 under M parity and N parity.

Superfield	M	N
Q, u^c, d^c	+	+
L, e^c	-	+
h, h^c	-	+
E_1, \bar{E}_1, S_1	+	+
$E_{2,3}, \bar{E}_{2,3}, S_{2,3}$	+	-
N^c	-	-

Since the λ_5 term of the SM is not available in supersymmetry, the equivalent $A^0 - H^0$

mass splitting is now achieved in one loop, from the effective $[(\tilde{N}_E^c)_1^\dagger (\tilde{N}_E^c)_{2,3}]^2$ term after supersymmetry breaking. Neutrino masses are then obtained in two loops. It may be noted that two-loop neutrino masses are also naturally obtained in a model of Z_3 dark matter [24]. Another variant of the $E_6/U(1)_N$ model has also been proposed [25] with the multiplicative conservation of baryon number.

In all of the above models of a special second scalar doublet, the Z_2 discrete symmetry is imposed by hand. Is it possible to obtain it from a gauge symmetry? The answer is yes, as shown in a recent explicit example [26]. The idea is to extend the MSSM with a new $U(1)_X$ gauge group, so that the usual R parity is automatic (i.e. not imposed by hand as in the MSSM), and the new Z_2 is the remnant of $U(1)_X$ breaking. This particular realization requires the addition of new superfields as shown below. Under $U(1)_X$, the MSSM superfields $(u, d), (\nu, e)$ are trivial; $u^c, (\phi_1^0, \phi_1^-)$ transform as n_2 , and $d^c, e^c, (\phi_2^+, \phi_2^0)$ as $-n_2$. For $U(1)_X$ to be anomaly-free, eleven copies of N_i are required.

Table 3: New particle content of $U(1)_X$ model.

Superfield	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_X$
$\eta_1 \equiv (\eta_1^0, \eta_1^-)$	$(1, 2, -1/2)$	$n_2/4$
$\eta_2 \equiv (\eta_2^+, \eta_2^0)$	$(1, 2, 1/2)$	$-n_2/4$
N_i	$(1, 1, 0)$	$n_2/4$
χ	$(1, 1, 0)$	$-3n_2/4$
S	$(1, 1, 0)$	$-n_2/2$
ζ	$(1, 1, 0)$	$3n_2/2$

In summary, the utility of a special second scalar doublet (η^+, η^0) with $\langle \eta^0 \rangle = 0$ has been discussed. It points to an exactly conserved Z_2 discrete symmetry, which may be important for understanding the interconnectedness of dark matter, radiative neutrino mass, leptogenesis, and grand unification. It predicts new particles at or below the TeV energy

scale which may be verifiable at the forthcoming Large Hadron Collider (LHC) at CERN.

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